Australian Academy of Science

REEF FUTURES ROUNDTABLES REPORT

AUGUST 2023

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Acknowledgement of Country

The Australian Academy of Science (the Academy) acknowledges and pays respects to the Ngunnawal people, the Traditional Owners of the lands on which the Academy office is located. The Academy also acknowledges and pays respects to the Traditional Owners and the Elders past and present and acknowledges emerging leaders of all the lands on which the Academy operates, and its Fellows live and work.

We acknowledge the continuing management and custodianship of Country across the Great Barrier Reef region by its Traditional Owners, whose rich cultures, heritage values, traditions, enduring connections and shared management efforts continue to protect land, sea and sky Country for future generations.

We recognise the continuous living culture of Aboriginal and Torres Strait Islander peoples—their diverse languages, customs and traditions, knowledges and systems—and the deep relationship and responsibility to Country as integral to their identity and culture.

We thank Traditional Owners for their enduring stewardship and protection of the Great Barrier Reef for thousands of generations—and for their ongoing guidance and partnership in the shared efforts to protect the Great Barrier Reef.

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Cover: A phytoplankton bloom in the Great Barrier Reef. CREDIT: NASA'S EARTH OBSERVATORY.

Table of abbreviations found in this report:

ABBREVIATION	MEANING
the Academy	Australian Academy of Science
COTS	Crown-of-thorns starfish
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCCEEW	Department of Climate Change, Energy, Environment and Water
GBR	The Great Barrier Reef (encompassing the GBR Marine Park, GBR Coast Marine Park and GBR World Heritage Area)
FPIC	Free, prior and informed consent
GBRMPA	Great Barrier Reef Marine Park Authority
IEP	Independent Expert Panel
SSP	Shared socio-economic pathways
Reef 2050 Plan	Reef 2050 Long-Term Sustainability Plan
TUMRA	Traditional Use of Marine Resources Agreements
UNESCO	United Nations Educational, Scientific and Cultural Organization

Image pages 4–5: Island with coral reef at sunrise on Great Barrier Reef. CREDIT: THE OCEAN AGENCY

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FOREWORD

Living systems are vulnerable to climate change. One such living system, a global icon, is in the primary care of Australians: the large and complex Great Barrier Reef (GBR).

The GBR has been affected in recent years by marine heatwaves and extreme weather events that have disrupted or damaged the ecological systems which define it. Worse, the intervals between disruptions are shortening as the planet continues to warm.

The question before us is straightforward: how can Australians support the GBR and increase its resilience in the face of climate change?

Of course, Australia must make a substantial and fair reduction in our own greenhouse gas emissions. But when we do, and even if global emissions were to cease overnight, the global average temperature will still climb before peaking and falling.

In that context, are we doing all that we can to support the GBR through these impacts? Do we know all we need to know, or all that we should know, to prepare the best evidence-based strategies to support the GBR?

The Australian Academy of Science (the Academy) was commissioned by the Department of Climate Change, Environment, Energy and Water to provide advice to the Reef 2050 Plan Independent Expert Panel on what we know, what we don't know and what we need to know as we manage the GBR ecosystem in the face of unrelenting climate change.

The project brought together three multidisciplinary expert-led roundtables to understand the compounding impacts of climate change on the ecosystem, to identify gaps and to understand the applicability of interventions in a changing climate.

The three roundtables were each co-chaired by two people, a Chair and a Traditional Knowledges Chair. As the Academy approached the task of planning this project it became immediately obvious that there was no separating nature and culture when it comes to the GBR. Land and sea cannot be separated. No priority can be selected on an ecological basis alone. Having a Traditional Knowledges co-Chair in each roundtable allowed for different sources of knowledge to be shared and to form a basis for a number of the observations featured in this report.

This report lays out a challenge: what could we do better? It interrogates the path we are currently on and reminds us that sticking to that path, simply because we started on it, may not offer the best solution for the GBR.

I would like to thank the four roundtable chairs: Ms Chrissy Grant (an Aboriginal Eastern Kuku Yalanji from the Jalun-warra clan and Torres Strait Islander Mualgal from Kubin on Moa Island Elder), Dr Steve Morton, Dr Beth Fulton and the Hon Dr Annabelle Bennett. Finally, I would like to express our gratitude to all the participants in the roundtables for contributing their expertise.

Professor Chennupati Jagadish AC PresAA FREng FTSE
President, Australian Academy of Science

EXECUTIVE SUMMARY

The Great Barrier Reef (GBR) is one of the great natural wonders of the world. It has been enjoyed by multiple generations since it formed after the last ice age. It has delivered social, cultural and economic benefit to millions of people.

The environment that formed the GBR is changing at a scale and pace never before experienced.

Global warming, elevated ocean temperatures, extreme weather events, ocean acidification, coastal development, land clearing that changes the rivers and streams that flow into the GBR waters, fishing, pollution and more all have an impact on what is a delicate, extraordinarily complex and vulnerable ecosystem. Most of this has occurred within the last 200 years.

There are intricate and interdependent ecosystems that comprise the GBR. These remarkable ecosystems require detailed understanding of the sensitivities and vulnerabilities of the multiple components if the most effective evidence-based actions are to be designed and implemented.

The Australian Academy of Science (the Academy) convened groups of experts to assess the likely outcomes for the GBR in three climate scenarios (near-term, and both low-emissions and high-emissions trajectories in the medium-term) to provide advice to the Independent Expert Panel (IEP) for the Reef 2050 Long-Term Sustainability Plan (Reef 2050 Plan).

The Academy held three roundtable discussions: the first on climate impacts on functions of the GBR (co-chaired by Dr Steve Morton); the second on interventions (co-chaired by Dr Beth Fulton); and the third on the future of the GBR (co-chaired by the Hon Dr Annabelle Bennett). Traditional Knowledges co-Chair Chrissy Grant participated in all three roundtables. There were 84 participants including scientists, engineers, Traditional Owners, lawyers, policy experts and social scientists. Discussions were supplemented by surveys and written contributions by participants on the day. Further details are provided in Appendix B.

If current greenhouse gas emissions trajectories are not reduced, and the planet therefore continues to warm, the species, habitats and ecosystems that make up the GBR will fundamentally change.

Efforts and resources have been put into the research and management of the GBR, but as we accept our national responsibility to care for this global icon, there is more that can be done, and needs to be done.

Existing interventions are important. They aim to buy time for reef ecosystems to adapt. Currently, there is no single known intervention, operating holistically and at-scale, for a sustainable and resilient GBR. There are, however, opportunities to align research and management efforts to create a whole that is greater than the sum of its parts.

Drawing on the discussions, surveys and written contributions, the following opportunities were identified:

1.

OPPORTUNITY 1.1

If gaps in knowledge in the high-emissions scenario were filled, including improved understanding of how different ecological functions might be impacted, communities could be better prepared for the anticipated disruptions to lives and livelihoods.

OPPORTUNITY 1.2

Extending the data on function and processes of ecosystems beyond corals, fish, seagrass and mangroves to include the GBR's other diverse functions would enable an understanding of when impacts from climate change will become irreversible.

OPPORTUNITY 1.3

Flow-on effects from climate impacts to cultures and customs are rapidly changing and mostly unknown, which makes prioritising where to intervene to protect areas of high cultural value to Traditional Owners difficult. This could be improved by ensuring transdisciplinary knowledge is integrated into prioritisation processes.

OPPORTUNITY 1.4

Indigenous peoples have adapted to a changing GBR, but the rate of change experienced at present and in future is unprecedented. Traditional Knowledges could provide a framework for managing a changing and adapting GBR.

2.

OPPORTUNITY 2.1

Techniques to advance existing research and development programs to develop new interventions will require expanded monitoring and modelling. This can provide information to support decision-making, noting that any prioritisation process should consider the urgency required to develop and deploy interventions.

OPPORTUNITY 2.2

There is enough knowledge now to ramp up research and development of interventions that will be effective in a high-emissions scenario. Combining interventions will be important for achieving maximum benefits when addressing climate impacts. When designing and implementing interventions, existing interventions and where there may be interactions could be considered.

3.

OPPORTUNITY 3.1

Standardising and centralising socio-ecological data could aid GBR management. Of particular importance will be understanding differing opinions between groups as to what values, regions or functions are most important for preservation or maintenance. If we can't save everything, what is able to be saved needs to be communicated and understood by all.

OPPORTUNITY 3.2

Greater alignment of communication strategies between organisations that research and manage the GBR could assist the public in understanding the reality of climate impacts and the risks of intervening and not intervening.

OPPORTUNITY 3.3

Relevant research organisations could form a consortium to agree on sector-wide data standards and sharing arrangements. Such agreements will allow for increased data sharing between organisations, and support better integration of existing and future research efforts.

OPPORTUNITY 3.4

If suitable regulation and laws are developed, which do not rely on political involvement to be implemented in full, a more evidence-informed system would be secured for the benefit of the GBR.

OPPORTUNITY 3.5

A comprehensive review of GBR management may offer opportunities to streamline processes that are currently decentralised to create a management setting that is fit for purpose and agile enough to react to a changing climate.

Coral bleaching with blue water on reef in Australia, Great Barrier Reef. CREDIT: THE OCEAN AGENCY

INTRODUCTION

The GBR is a natural wonder of the world, home to about 10% of the world's coral reef ecosystems. Climate change and local stressors are challenging the GBR's resilience and ability to sustain a healthy ecosystem.

Australia has a unique opportunity to lead the global scientific community in climate-affected systems weakened by climate change. Advancing such scientific knowledge aims to support the resilience of these large natural ecosystems in a changing climate. Ecological and socio-ecological interventions are expanding current knowledge which is being applied through a range of programs that put specific and targeted activities into practice.[1]

Reef Futures Roundtables scope

The Academy was engaged by the Department of Climate Change, Energy, Environment and Water (DCCEEW) to provide input to the IEP, convened under the Reef 2050 Plan. The IEP assists in understanding differential impacts of climate change across the GBR under different climate scenarios, and in the context of emerging intervention technologies.

The Reef Futures project brought together experts across a range of disciplines to understand the compounding impacts of climate change on species, habitats, ecosystems and peoples across the GBR (coastal, terrestrial and marine areas), and their implications for developing a hierarchy of interventions, through three roundtables.

Traditional Knowledges

Indigenous peoples have built relational ways of knowing, doing and being with the land, sea, waters and skies, known as Country, over millennia.[2] Country is more than just place, it is part of the Australian identity.[3] Integrating the rich sources of local or Traditional Knowledges is not only morally required but brings diverse benefits to research and knowledge use in decision-making, management and conservation.[4-9]

The relevance of Traditional Knowledges is particularly important to better understand and adapt to the impacts of climate change, as Traditional Owners have long adapted to a changing GBR which may provide a framework for future management.[10] Traditional Owners have witnessed the formation of the GBR in a series of steps over thousands of years. The Reef 2050 Plan outlines a need for greater understanding of Indigenous peoples' world views to working together on policy dilemmas and to empower all peoples to deliver solutions.

Method

Three roundtables were held at the Shine Dome in Canberra and online between March and May 2023. There was a nomination process for each roundtable where peak organisations were invited to nominate participants who fit the scope of expertise required. Nominations were assessed and selected participants were invited based on their expertise (Appendix A).

Prior to each roundtable, participants completed a survey, and were given a set of climate storylines outlining the differences between present and future climate scenarios. A storylines methodology allows for different plausible futures under alternative conditions.[11-14] The GBR-specific storylines were founded on plausible emissions scenarios, climate indicators and evidence from assessment reports from the Intergovernmental Panel on Climate Change. The three climate scenarios were:

1. Near-future (2023–2040) – these impacts are already 'baked in' to the system, with a global average temperature increase of 1.2 to 1.8 degrees relative to 1850–1900
2. Medium-term future (2040–2060) low-emissions scenario – global average temperature increase of 1.2 to 2.2 degrees relative to 1850–1900 [shared socioeconomic pathway (SSP)1-2.6]
3. Medium-term future (2040–2060) high-emissions scenario – global average temperature increase of 1.7 to 2.6 degrees relative to 1850–1900 [SSP3-7.0].

The storyline scenarios were used as a stimulus for the roundtable discussions and are referred to in this report where low-emissions and high-emissions futures are compared.

Discussions in the roundtable were recorded only for note-taking and qualitative analysis purposes, with all contributions from participants deidentified. The procedure was in line with the Academy principles of science policy advice, particularly the principle of independence. This independence allowed for free contribution of evidence from experts in the roundtables, so that the advice would not be subject to any form of interference in its drafting or its conclusions.

Specialist divers removing crown-of-thorns starfish from the Great Barrier Reef.
CREDIT: M. CURNOCK / COPYRIGHT COMMONWEALTH OF AUSTRALIA (GBRMPA)

Reef Futures: Expertise and Chairs

The series of roundtables were chaired by Ms Chrissy Grant (an Aboriginal Eastern Kuku Yalanji from the Jalun-warra clan and Torres Strait Islander Mualgal from Kubin on Moa Island Elder), Dr Steve Morton (formerly CSIRO), Dr Beth Fulton (CSIRO), and the Hon Dr Annabelle Bennett (Bond University). The expertise included both government and non-government representatives, Indigenous representation, marine and climate scientists, social scientists, economists, modellers, decision scientists and others.

Roundtable One had 26 participants, including specialists in modelling and predictions, marine and terrestrial ecology, marine biology, coral ecology (including monitoring), climatology, seagrass, water quality, threatened species and Traditional Knowledges (including socio-ecological research).

Roundtable Two had 29 participants with expertise in GBR catchment and terrestrial ecological systems and management, emerging intervention technologies (cloud brightening, cryopreservation, robotics), policy, regulation, change management, and industry engagement. One person from Roundtable One also participated in Roundtable Two.

Following the first two roundtables, provocations were developed for the participants of Roundtable Three.[15] This approach was adopted to stimulate collaborative discussion by presenting a set of challenges via provocative statements to encourage out-of-the-box thinking and diverse perspectives.

Roundtable Three had 29 participants. This included returning participants and new participants with combined expertise on Traditional Knowledges, future management, integrated societal governance, climate science, ecosystem modelling, regulation, law and permits, spatial risk assessment, and United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage.

A research scientist takes note of coral growth on Wheeler Reef. CREDIT: A. CHINN / COMMONWEALTH OF AUSTRALIA (GBRMPA)

CHAPTER ONE:
CLIMATE CHANGE AND LOCAL STRESSOR IMPACTS ON THE GREAT BARRIER REEF

The GBR is a complex amalgamation of ecosystems, habitats, biocultural values, taxonomic groups, ecological processes and cultural heritage. The ecological state of the GBR has undergone various changes in the past and will continue to change in the future. The current state of the GBR and rate of change is unprecedented.

The science and research community in Australia has played a crucial role in enhancing our understanding of the GBR and its ecological, social, economic and cultural dynamics.

Image: Reticulated damsel feeding on a coral. CREDIT: ANDRIISLONCHAK / ADOBE

Reef ecological functions and processes

Identifying key ecological functions is complex, and prioritising conservation of different key species, habitats and ecosystems is difficult. If choices are made about where intervention should be directed to preserve functions, these functions need to be better understood. Without this fundamental understanding, actions intended to preserve functions could have unintended consequences.

Participants identified that GBR science is focused on corals, fish, seagrass and mangroves as key ecological components that contribute to the functional health of the GBR. These components are impacted by climate change. Roundtable participants indicated the focus, particularly on corals, is historical. This focus is due to assets like biodiversity, cultural importance and aesthetic value (leading to public interest), and associated revenues from tourism and fisheries.

For the near-future scenario to 2040, there will be moderate impact on ecosystems. The 2060 low-emissions scenario is similar, with a growing frequency of extreme weather events that will prevent time for recovery and have unknown impacts on the systems.

The 2060 high-emissions scenario had a large majority of high-impact responses.

The following critical processes were identified as being impacted:

- calcification
- recruitment (in reference to both coral and fish)
- symbiosis.

A categorisation of these processes listed by participants as part of this exercise showed 60% of the listed processes were ecological, 28% were physical and 12% were chemical.

Ocean warming and severe tropical cyclones were listed as the key stressors. Coral reefs and seagrass returned the most responses for stressor-impacted ecosystems. For coral reefs, the most frequently listed stressors were ocean warming and severe storms/tropical cyclones. For seagrass, ocean warming was the most frequently listed stressor, followed by pollutants.

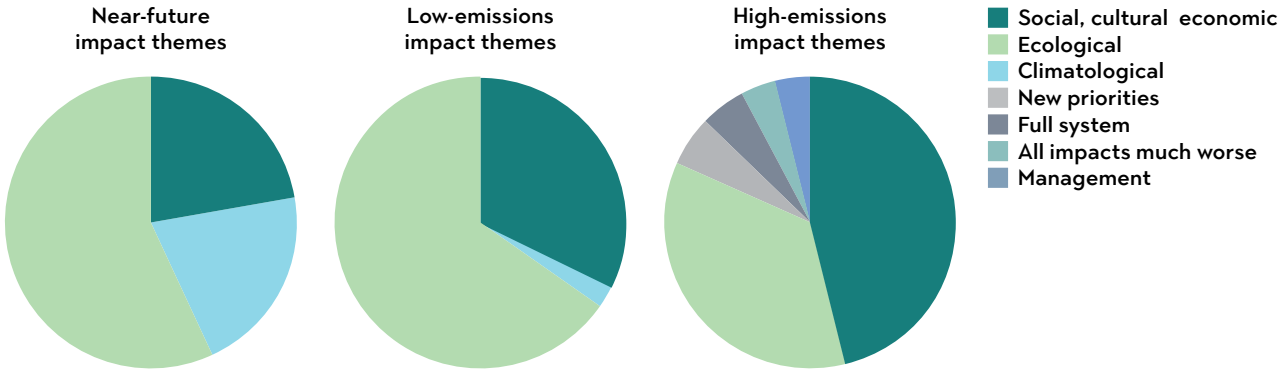
Climate impacts were differentiated across scenarios for ecological processes, functional integrity, and socio-ecological (social, cultural and economic) functions e.g. fish nurseries and sediment stabilisation.

The resulting effects of changes to GBR functions on social, cultural and economic values were undetermined. Traditional Owners reiterated their holistic understanding of the GBR and the all-encompassing features and innate interconnections between ecosystems, peoples and the GBR. This includes customary activities, songlines, stories, totems and spirituality. A video written and narrated by Traditional Owners of the GBR was shown to demonstrate this cultural and spiritual connection to the GBR during Roundtable One.

Participants offered their knowledge of existing and anticipated climate change impacts, outlined in Table 1.

Table 1: Impacts of climate scenarios on GBR values

	NEAR FUTURE 2023–2040	MEDIUM-TERM FUTURE 2040–2060	
		High emissions	Low emissions
Ecological	Heightened impacts (foremost on coral reefs and seagrass habitats, and individual species groups like fish, turtles and dugongs) from increasing heatwaves and bleaching events, damages from tropical cyclones. Also, erosion and associated effects on shorelines and water quality.	Ecological thresholds for individual species are approached or will be exceeded irreversibly, biodiversity will continue to decline and more habitats will be lost or degraded. There will be potential severe impacts on coastal areas, catchments and the 900 GBR islands from increased coastal erosion and the release of blue carbon from degraded coastal ecosystems. The full GBR system will be affected by fundamental and irreversible changes in communities, habitats and socio-ecological systems.	Losses in ecological habitats and species (coral and seagrass) will occur with more effects on species distribution and composition. Corals will undergo greater decline, with more regular bleaching events and less recovery time between events. Seagrass habitats will further decline as will the broader ecosystem functions of the GBR.
Economic	Tourism industry impacted by perceptions of declining GBR health. Reductions in fisheries were also a concern.	Near complete or complete loss of key economic activities, including fisheries and existing tourism activities (however these may adapt).	Economic impacts to GBR and coastal communities (e.g. through less sustainable fisheries and tourism), and adjustments (e.g. towards new sites or coral gardens).
Social and cultural	Loss of cultural totems and practices, loss of sacred Indigenous sites from flooding, and the wider impacts on Indigenous cultures, values and practices including between Indigenous communities and research and management.	Loss of functions, including coastal communities and Traditional Knowledges, were mentioned more than ecological impacts. Negative impacts are expected, including on sentiment, culture and human wellbeing, as well as a loss of motivation and hope in the population with flow-on effects for support of management efforts.	Increasing threats to Traditional values and practices, food availability, wellbeing, and important totem species.



OBSERVATION

In the near-term and the medium-term low-emissions scenario, the impacts discussed were primarily ecological. In the medium-term high-emissions scenario, the impacts discussed became more focused on functions that impacted the people that live adjacent to, or on the GBR. In the high-emissions scenario, disruption to people's lives and livelihoods was the leading concern.

OPPORTUNITY

If gaps in knowledge in the high-emissions scenario were filled, including an improved understanding of how different ecological functions might be impacted, communities could be better prepared for the anticipated disruptions to lives and livelihoods.

1.1

The significance of corals as the ecosystem engineers of coral reefs has led to a large body of ecological and biological knowledge focused on these organisms. In this way, coral dominates the research landscape—although a good deal of attention has also focused on seagrass, fish and turtles. Other parts of the ecosystem, both on land and at sea, are comparatively under-researched.

There are several possible explanations, including:

1. Direct and cascading social and cultural effects are interlinked with on economic and aesthetic values. In turn, much of the aesthetic and economic value of the GBR is derived from coral reefs.[16]
2. The pathways for integrating Traditional Knowledges and social factors into decision-making processes are less developed than the already well-established scientific pathway for contemporary ecological knowledge, particularly corals and reef systems.
3. The handful of Reef-focused institutions often 'patch protect' research data for commercial or other reasons, which can risk siloing of information at project or institutional levels.

Further analysis of these three points will reduce the levels of uncertainty for the high-emissions scenario, which features prominent gaps in understanding. These include:

- responses of ecological functions
- ecological response of ecosystem condition (including the flow-on implications of low coral cover)
- loss of spiritual and cultural heritage sites for Indigenous peoples
- economic impacts on national and state economies via fishing and tourism
- local communities impacted by coastal geomorphological change.

Climate change impacts could be irreversible

Irreversible impacts from climate change on GBR ecological and socio-ecological systems are probable. The exact form of these impacts, which will be observed in communities, habitats and ecosystems, is undetermined, but will challenge the system's resilience and cohesiveness. These irreversible impacts will emerge if a threshold is reached. Reaching such a threshold under the near-future and low-emissions scenarios is possible around mid-century, regardless of whether global emissions stabilise.

Cascading ecological impacts (e.g. coral decline affecting fish and other habitat functions, seagrass decline impacting green turtles and dugongs) and interactions with other stressors (e.g. extreme events and ecosystem degradation increasing erosion and sediment loads, and decreasing water quality) mean passing a threshold is a realistic threat. Passing a threshold in one part or process of the system may have flow-on effects, pushing other parts of the system closer to (or beyond) their own thresholds.

> 'At some point on the spectrum of climate stress, more knowledge will not help us prevent damage—it will then be a matter of helping people adapt to a changing/degraded system, ideally proactively.'

Participants highlighted that under the high-emissions scenario, impacts will be greater, longer lasting and more costly. In a high-emissions scenario, the risk to reach and exceed thresholds for different parts of the GBR system is higher and likely irreversible. Non-linear effects from climate change in a high-emissions scenario and the effects of multiple or combined stressors on the ecosystem remain unclear.

It is difficult to predict impacts of future oceanic conditions, stratification and extreme events under the high-emissions storyline, as those conditions are substantially different from conditions captured by extant monitoring. Maintaining the liveability of coastal communities will mean adapting to changes in coastal ecosystems and land use, and a new understanding of the connections between GBR health and social and cultural management requirements.

> 'We have insufficient knowledge of thresholds/tipping points—at what levels do these occur, how rapidly will change occur, what are the processes?'

OBSERVATION **1.2**

Limited information about potential climate impacts in the high-emissions scenario can be attributed to a variety of reasons. The complexity is compounded because it is harder to rely on patterns and lessons from historical monitoring, as there are more cascading and interacting impacts.

OPPORTUNITY

Extending the data on function and processes of ecosystems beyond corals, fish, seagrass and mangroves to include the GBR's other diverse functions would enable greater understanding of when climate change impacts will become irreversible.

SOCIAL AND CULTURAL IMPACTS REQUIRE MORE UNDERSTANDING

Impacts of climate change on future socio-ecological systems require more understanding. Flow-on societal effects could be:

- a reduction in human wellbeing
- the loss of Country and culture
- loss of or change to coastal communities' identities and livelihoods
- loss of public confidence in science
- loss of public confidence in environmental policy.

Similarly, the flow-on effects to cultures and customs are changing, with existing data becoming outdated. This suggests a need for more social research and better integration of transdisciplinary knowledge. Participants suggested solutions to determine the effectiveness of current priorities before considering new ones, such as impacts on people and society. They also suggested prioritising efforts to remove any knowledge gaps.

Roundtable participants identified several full and partial knowledge gaps in our understanding of the GBR ecosystem, including which functions and processes are vital for a resilient system. How each function interacts with the socio-ecological systems and Indigenous world view systems remains less certain.

OBSERVATION

1.3

It is imperative to continue engaging with various stakeholders, including Aboriginal and Torres Strait Islander peoples, governments, non-government organisations, and community groups, to effectively address the impacts of climate change and local stressors. Stakeholders' collective involvement will be essential for both mitigating and adapting to these challenges.

OPPORTUNITY

Flow-on effects from climate impacts to cultures and customs are rapidly changing and mostly unknown, which makes prioritising where to intervene to protect areas of high cultural value to Traditional Owners difficult. This could be improved by ensuring transdisciplinary knowledge is integrated into prioritisation processes.

Near-term and medium-term knowledge gaps

Responding to threats to the GBR with the most effective action requires comprehensive knowledge of the ecosystem, its species and how the climate is changing. Currently, this understanding is incomplete; knowledge gaps identified for the near-term and medium-term future scenarios include:

- ecological knowledge related to fundamental ecosystem functions and processes
- individual species' interactions, tolerance to change, biological thresholds and ability to adapt
- effects of multiple or combined stressors as gleaned from past extreme weather events
- climatological understanding of the impacts and intensity of future events
- uncertainty in models and the scale of modelling.

In a high-emissions future scenario, where the GBR system would be physically different to today, further knowledge gaps become apparent. These are dominated by management and research questions. For example, what would be the recovery potential and ecological functioning of new, low-coral-cover systems? A further challenge will be integrating different streams of information to compile clear and comprehensive messaging and ways to communicate to the public.

Further gaps include:

- impacts on social and cultural values that rely on the GBR's ecosystems, including impacts on Traditional Owner wellbeing
- knowledge on ecosystem interactions, connectivity and potential tipping points, and species adaptations or thresholds—particularly what a loss of coral will mean for the ecosystem and ecosystem services
- inclusion of Traditional Knowledges and understanding of flow-on effects to coastal communities.

Participants highlighted the need to prioritise which gaps to fill first, by determining which ones are hindering decisions.

> 'Under high emissions reefs may be the last of our worries. [...] We need a functionally informed reality check so we can move forward to a non-coral dominated world and still maximise the services we need.'

Traditional Owner partnerships to address climate change

Despite growing recognition of the relevance of Traditional Knowledges and Indigenous world views[17] to environmental understanding and management, current practices often lack appropriate cooperation with Traditional Owners. While Australian law and regulations support the rights of Traditional Owners, principles of free, prior and informed consent (FPIC) are often ignored, incomplete or undermined.

> 'Our customary activities, songlines and stories as well as important cultural food sources are linked to our Country. To the environment. As we see changes to the environment that we are unable to adapt to, we need to think about far-reaching impacts to First Nations people.'

Traditional Owners understand the connection between land and sea and the interconnectedness of ecological and socio-ecological functioning. This understanding, rooted in Traditional Knowledges of the GBR, could guide management frameworks.

> 'Our records, even our longest, are short. Indigenous knowledge has a lot to add.'

OBSERVATION

Indigenous peoples have developed holistic world views over thousands of years. This Traditional Knowledges blurs the boundaries between land and sea, nature and culture, regarding a system like the GBR—and its communities—as a whole.

OPPORTUNITY

Indigenous peoples have adapted to a changing GBR, but the rate of change that is being experienced and will be experienced is unprecedented. Traditional Knowledges could provide a framework for managing a changing and adapting GBR.

1.4

CHAPTER TWO: INTERVENTIONS AS RESPONSES TO KEY THREATS

Australia has invested in environmental restoration and intervention science for more than two decades. Restoration of wetlands, shellfish beds and mangroves are well-established components of national environmental policy and management tools.[18] Climate change impacts have accelerated the need to increase the development and implementation of interventions.

2.1

OBSERVATION

Interventions can both use data and generate data. Existing interventions aim to buy time for reef ecosystems to adapt. However, the level of contribution interventions could make towards building a resilient GBR is unclear at present.

OPPORTUNITY

Advancing existing research and development programs to develop new interventions will require expanded monitoring and modelling. This can provide information to support decision-making, noting that any prioritisation process should consider the urgency required to develop and deploy interventions.

Image: Nesting sooty and masked terns at Taylor Cay, near Mission Beach. CREDIT: MATT CURNOCK

Reef interventions

All pre-roundtable survey respondents agreed that there should be intervention on the GBR ecosystem. Interventions not only aim to build resilience in the GBR and connected ecosystems, but also provide valuable scientific data. The research and development of interventions occurs on a range of scales, largely focused on catchment and land management (e.g. restoration and land use planning) and corals (e.g. deployment of enhanced corals). Ecological interventions are predominantly water focused and directly or indirectly target corals.

Coral interventions, first established as small-scale coral gardening, have advanced in recent years. Hardy corals, coral rubble stabilisation, genetic diversity in asexual propagation (coral IVF) and artificial reefs are examples of coral interventions.[19- 21]

Water-focused interventions listed by participants include:

- solar radiation management (e.g. shading, fogging, cooling techniques)
- assisted gene flows, cryogenics and biobanks
- rubble stabilisation
- crown-of-thorns starfish (COTS) control
- larval collection and settlement (coral IVF)
- artificial habitat
- probiotics
- heterotrophic feeding/food manipulation
- alkalinity manipulation
- microbiome manipulation
- manipulation of symbionts
- coral breeding for enhanced tolerance
- transplanting corals from warmer climates (assisted migration).

Terrestrial interventions listed by participants included a range of land management practices with potential impacts on GBR water quality, such as:

- land, gully, and hillslope remediation (e.g. run-off reduction)
- implementation of grazing and groundcover best management practices
- control and minimisation of coastal bushfires
- watering of dehydrated shoreline mangroves
- enhanced efficiency fertilisers
- unsealed road management
- adaptation and retreat of constructed shoreline barriers
- minimisation of the use of harmful agricultural chemicals and nutrient loads
- bioreactors for nutrient reduction in run-off, and improved farming practices.

Programs supporting these terrestrial interventions include:

- grants to support land managers
- extension services in GBR catchments including training and assistance to trial new practices
- landscape repair programs
- market-based instruments (e.g. Reef Credits Scheme).

Participants mostly agreed that existing and emerging interventions would sustain ecosystem functions in near-future and low-emissions scenarios, although there was less agreement and certainty in the high-emissions scenario.

Interventions may also require a trade-off between target and location of intervention and evaluation of the potential loss of other parts of the system. Such trade-offs have the potential to lead to conflict and present risks to an evidence-based prioritisation process aligned with public support for actions.

> 'Models are the only way to understand reef futures and test the risks and benefits of various interventions. But let's be careful to not hide behind the need for more information before we can say or do anything.'

Interventions in the near-future (2023–2040) will largely remain effective—in particular, the coral-related interventions including COTS control, rubble stabilisation, coral aquaculture and larval seeding. Catchment-oriented approaches such as those addressing water quality and farming processes, as well as marine park zoning and fisheries management, were considered to remain relevant and of importance in the near term.

Interventions in the low-emissions scenario (2040–2060) will need to increasingly target adaptation for GBR catchment health. This includes interventions related to nutrient inputs, and seeding and deployment of enhanced heat-tolerant corals. The participants were in broad agreement that any intervention was to 'buy time for reef ecosystems to adapt', and that there were no known interventions that would be a holistic, at-scale 'silver bullet' for a sustainable and resilient GBR. Additional focus areas for interventions were:

- non-ecological interventions, such as those that target ecological, economic, social and cultural values
- the resilience of ecosystems
- targeting areas with high vulnerability
- improved efficacy and lower risk of harm.

Coral-related interventions remained the most described effective interventions for a low-emissions medium-term future. However, it was noted that coral gardening (without enhancement) may not be an effective method for restoration at scale.

> 'The tools we have had that have served us well over the past four decades need to be amplified and applied based on what is likely to happen rather than what has happened.'

Interventions in the high-emissions scenario (2040–2060) will need to focus on catchment management (including land restoration and landscape repair) and corals (seeding enhanced thermally tolerant corals). Deployment of enhanced corals through aquaculture and synthetic biology and at local scale was raised. Emerging coral-focused interventions will include more genetic and assisted evolution strategies such as microbiome or symbiont manipulation, probiotics, and interspecific and intraspecific hybridisation and breeding. Marine Park zoning and COTS management were named, as well as socio-economic planning for change—that is, helping people navigate the reality of transformed reefs.

The long list of unknowns in the high-emissions scenario led to polarised perspectives on what interventions would become obsolete, ranging from 'none' to 'most' interventions. Current interventions for protecting and restoring coral habitat (including coral gardening without enhancement and COTS control) were suggested as possibly becoming obsolete when environmental conditions are unsuited for high coral cover.

Dealing with a high-emissions scenario will require multiple interventions of multiple types operating across an extensive range of spatial scales. The co-benefits and conflicts of intervention methods and technologies are important considerations. Synergistic interventions, leading to compounding benefits, will be valuable and important to identify.

OBSERVATION

2.2

More knowledge and better modelling of ecological processes must be accompanied by tools to respond to changes. There are no interventions—either existing or emerging—that all participants agreed would still be effective in the high-emissions scenario.

OPPORTUNITY

There is enough knowledge to ramp up research and development of interventions that will be effective in a high-emissions scenario now. Combining interventions will be important for achieving maximum benefits while addressing climate impacts. When designing and implementing new interventions, the presence of existing interventions and potential for interactions could be considered.

Hardy Reef in the Whitsundays. CREDIT: MARCO BRIVIO PHOTOGRAPHY

Intervention knowledge gaps: Intervention combinations

Combining interventions could enable a greater chance of addressing key threats. Existing intervention measures, such as zoning, Traditional Owner engagement and COTS control can support other interventions when deployed in combination. Rubble stabilisation, solar geoengineering and optimising heterotrophy are interventions that complement and support enhanced coral propagation. Additionally, aquaculture production of coral larvae and deployment using wild and brood stock colonies can be accompanied by assisted evolution and cryopreservation. Land-based combination interventions, such as drainage, revegetation and water quality improvement, are also effective combinations.

However, participants advised caution over potential conflict that may arise on the location and timeline of many interventions, particularly when deployed in combination. This may require trade-offs over targeted ecosystems, location on the GBR (i.e. where within the 344,400 square kilometre area), and allocation or prioritisation of research and resources. Further trade-offs emerge when considering catchment-based interventions, for example between land development (including dams and energy transition), and land clearing—which can have negative impacts on water quality, sediment loads and nitrogen run-off. There is a risk of unintended marine-based consequences in altering species distribution and diversity. For example, translocating coral species risks introducing superweeds or species susceptible to storm damage, while restoring coral cover could be inadvertently undertaken in places prone to COTS outbreaks.

> 'Even with all the best ideas that are on the drawing board at the moment—which are not yet finished being developed—you are still gonna have a relatively small capacity. Massive compared to [capacity] globally but small compared to the size of a system of the size of Italy.'

Participants highlighted diverse gaps in intervention knowledge and practice, for example, in approaches, field trials, efficacy, risk appetite and acceptance, implementation, cost-benefit feasibility, and scalability. Intervention effectiveness and prioritising what to protect with interventions are key gaps. Likewise, the level of contribution interventions could make towards building a resilient GBR is unclear at present At an individual reef scale, there is evidence of successful rehabilitation—but how that will continue and how it will scale to the whole GBR remains unknown. Interventions are unlikely to preserve the current reef state in entirety.

Fundamental ecological research to flesh out our understanding of the Reef ecosystem, species and land-sea connectivity will also aid intervention development, as well as bettering our understanding of how species and habitats might react (source-sink dynamics) and the effects on sediments, nutrients and water quality.

SOCIAL DIMENSIONS OF INTERVENTIONS MUST ALSO BE CONSIDERED

Participants raised questions about existing management and regulatory ability to adapt under different scenarios, where contentious changes may be necessary (e.g. addition of increasing no-take zones, trade-offs between land management/managers and farming practices). Further, information on risk assessments, public and scientific appetite for interventions, and motivation for tackling GBR challenges mainly exists in grey literature. If peer-reviewed, these valuable details could support advanced decision frameworks to manage interventions.

Finally, participants highlighted that public awareness of future potential losses is necessary, because severe climate impacts could require higher-risk, larger-scale interventions that may not currently be socially acceptable.

Lessons from Traditional Knowledges

Partnerships with Indigenous peoples in co-design, prioritisation and application of interventions are at the heart of future GBR interventions. Weaving together Traditional Knowledges and contemporary science could assist with operationalising a decision framework with a fast track for intervention testing and upscaling. Interventions could include catchment revegetation and at-scale deployment of 'safe' thermally tolerant corals at jointly negotiated sites.

Risks to the biocultural land and seascape could be better understood. Truth telling to public and bringing them along the journey of scientific and management thought will be critical to nurture understanding, gain support for action and allow communities to prepare for future realities. Dignity of choice was a strong theme imparted by roundtable contributors. As one participant said:

> 'Traditional Owners actually, ethically and morally need a conversation around what if the Reef dies, what if Country dies? What if the direst situation happens and how will people prepare for that?'

Traditional Owner and community engagement were named as barriers to intervention deployment, but also as enablers. Traditional Owner partnerships built on meaningful cooperation require Traditional Owner capacity, willingness to share knowledge and FPIC.

CHAPTER THREE: **REEF FUTURES**

A synthesis of Roundtables One and Two informed a high-level discussion at Roundtable Three, exploring priority areas and management strategies to effectively support the GBR. Interactions or conflicts between interventions and ecological, social and cultural functions were also explored, with the aim of better understanding how to sustain the GBR functioning to the maximum possible extent under different climate futures.

Participants were challenged by a range of provocation statements. These acted as stimuli to provoke practical insights into GBR management, including its challenges, knowledge gaps and ideas for change. Roundtable Three reiterated the need for a more agile and evidence-informed prioritisation of management actions. This requires identifying ways of integrating different existing entities, knowledges and actors to provide a set of synergistic management tools.

Prioritisation of actions, species and locations will be needed. These may be defined by ecological values including biodiversity, resilience and connectivity. They may also be informed by the Outstanding Universal Values and the attributes that hold these values, for which the GBR was declared an UNESCO World Heritage Site. Economic and Indigenous values also need to be prioritised, including protecting totem species and sites. These values may overlap or be conflicting. Tourism and fisheries

Image: Turtle on the Great Barrier Reef, Australia. CREDIT: JORDAN ROBINS / OCEAN IMAGE BANK

(commercial and recreational) values should also be taken into consideration, as well as climate change refugia sites deemed ecologically important.

OBSERVATION

3.1

While there are existing prioritisation processes to determine vulnerable areas of the GBR and where intervention is needed, these processes are not clear to the public.

OPPORTUNITY

Standardising and centralising socio-ecological data could aid GBR management. Of particular importance will be understanding differing opinions between groups as to what values, regions or functions are most important for preservation or protection. If we can't save everything, what we can save needs to be communicated and understood by all.

Communication, risk and social licence

The ecological complexities and connections in the GBR system are not well understood by the public. Good scientific communication practices around risk should narrow existing gaps in public understanding of threats, impacts and urgency. A key message that emerged from roundtable discussions was the need to bring the public along on the journey of understanding and decision-making.

OBSERVATION

3.2

In attempting to attract attention and funding to their research, researchers may present mixed messages relating to the state of the GBR and its long-term outlook, and may present messages that are out of alignment with other organisations.

OPPORTUNITY

Greater alignment of communication strategies between organisations that research and manage the GBR could assist the public in understanding the reality of climate impacts and the risks of intervening and not intervening.

At the science-policy interface, researchers need to be 'honest brokers'[22] presenting all lines of evidence and communicating the reality of the GBR's future in the face of climate impacts. Beyond this, evidence-based science communication efforts will help the public understand the complexity and scale of the GBR, the sum and variability of threats, and the need for interventions. One participant said, '*People must understand the risk of NOT intervening before they can consider the risk of intervening.*' Mitigating this risk requires effective communication with a united voice and clear key messages.

Participants noted that although consistent and clear government messaging is needed, the government is not necessarily a trusted voice in many public spaces. Embedding key messages into grassroots communications is needed for efficacy.

Holistic data integration: Digital twin

A digital twin of the entire GBR could present a novel, more holistic and closer to real-time management tool. This could enable prioritisation of interventions and management efforts in a rapidly changing environment. However, it would require investment and sector coordination on an unprecedented scale.

Participants highlighted that this concept, or at least components of it, somewhat exists in projects such as eReefs. The mosaic of existing models would need to be integrated and expanded if it were to consider the many habitats, species types and interacting human dimensions making up the larger Reef system. Such an exercise would have value even at intermediate steps—simply joining together what is already there and allowing it to be easily interrogated to answer decision-maker questions would be immensely useful.

Improving the current modelling, monitoring and integration of existing datasets (e.g. Reef 2050 Integrated Monitoring and Reporting Program (RIMReP, GBRMPA), Integrated Ocean Stewardship (CSIRO), Reef Restoration and Adaptation Program (RRAP), Integrated Marine Observing System (CSIRO) and others) could help support better management decisions in the face of changing threats. For instance, improved modelling could facilitate better targeting of interventions or real-time interventions during episodic events, such as mass bleaching or tropical cyclones.

OBSERVATION

There are many research groups leading monitoring and modelling efforts related to the GBR, but there is no formal agreement between research groups regarding data standards and sharing.

OPPORTUNITY

Relevant research organisations could form a consortium to agree on sector-wide data standards and sharing arrangements. Such agreements would support better integration of existing and future research efforts.

Expanded monitoring and better integration of datasets and models could improve the ability to evaluate the benefits and risks of interventions at local and regional levels, provide additional data for testing interventions and scenarios, and warn against immediate near-term impacts.

Any future digital twin would have to consider much more than current models, which are focused on corals and catchments, expanding to incorporate a greater range of ecological, socio-ecological and socio-economic components.

The decentralised structure of GBR institutions means much current collaboration is facilitated by relationships between individuals. Roundtable participants were forthcoming in their willingness to collaborate across institutions (i.e. data sharing, modelling, etc.) within the remit of each institution.

Scuba diver at John Brewer Reef, near Townsville. CREDIT: MATT CURNOCK

Law, policy and regulatory settings

Regulation and policy settings were a recurrent theme of the three roundtables, including technical, institutional and legislative processes. In a pre-roundtable survey, 88% of participants agreed with the statement that there should be a comprehensive review of GBR management and 82% agreed to revising GBR management zoning plans to encompass catchments to deep water.

BARRIERS

There are several barriers preventing the full implementation of the regulations and laws:

- It is unclear which existing laws and regulations support the development of interventions, and to what extent they do so, as interventions are scaled up from pilot research.
- Current permitting processes lack the capacity to make decisions based on weighing up risks, benefits or competing outcomes. Instead there is a focus on the risks created by the intervention (i.e. restoration activities face the same permitting questions as an extractive or destructive activity, preventing timely action).
- A lack of political will to implement the regulations and laws allows upstream activities that are in opposition to the intent of existing laws, ultimately negatively impacting the GBR.
- An overlap with existing cross-jurisdictional regulation reaching into the catchments adds complexity to conservation science in coastal jurisdictions (e.g. harmonising seagrass and mangrove protection).
- There is difficulty in implementing new management processes and structures.
- There is concern over current investment in water quality, since even the best water quality alone cannot prevent corals from bleaching.
- Undermining of investment in protection of the Wet Tropics' own cultural and ecological values occurs.

OBSERVATION

3.4

If political will is preventing the implementation of regulations and laws that are designed to protect the GBR ecosystems, then the design of this system is not allowing for evidence-informed action in the best interest of the environment.

OPPORTUNITY

If suitable regulation and law are developed which do not rely on political involvement to be implemented in full, a more evidence-informed system would be secured for the benefit of the GBR.

LAW AND REGULATION

The risk of doing nothing is the biggest risk of all. Currently, policy is taking time to catch up. The speed of intervention will likely increase, and regulators need to be able to keep pace.

Existing law and regulations have capacity to address some of the barriers fully functioning regulatory process, including legislation, can provide:

- inclusive engagement processes that fully encompass co-design, co-development and co-delivery, including FPIC from Traditional Custodians
- accountability mechanisms that further enhance trust in research and programmes
- promotion of social acceptance
- incentivisation of research and development programs through funding mechanisms and by providing fit-for-purpose assessment and approval processes.

> 'We do have powers in our act that we have chosen not to actually use as much in the last 15 years [...]. The appetite both of public and government to do better to respond to and address the problems is there. But we are not there yet.'

OPPORTUNITIES

There are several opportunities that a comprehensive, independent review of GBR management could provide, including:

- increasing management agility
- enforcing a fuller suite of existing sections of legislation and policy
- increasing political will—and by extension public support—to effectively manage existing regulations and future interventions.

> 'We have a lot of the tools that we have been talking about already. [...] There are lots of things we can do and we can be agile for. [...] It really depends upon politically—and by association what the communities believe—what is actually necessary."

OBSERVATION

3.5

The GBR management system is complex and decentralised. It was established before there was understanding of how climate change would impact the GBR and is not built with the agility required to adapt to rapidly evolving climate impacts.

OPPORTUNITY

A comprehensive review of GBR management may offer opportunities to streamline processes that are currently decentralised to create a management setting that is fit for purpose and agile enough to react to a changing climate.

AREAS OF OPPORTUNITY

Key areas of opportunity were identified as follows:

OPPORTUNITY 1.1

1.

If gaps in knowledge in the high-emissions scenario were filled, including improved understanding of how different ecological functions might be impacted, communities could be better prepared for the anticipated disruptions to lives and livelihoods.

The GBR so far has shown some mild resilience to environmental variation and climate change impacts, but to what extent that resilience will be maintained in both low-emissions and high-emissions scenarios is unknown. Monitoring can inform responses, but also provides the best possible means of detecting change as rapidly as possible.

OPPORTUNITY 1.2

Extending the data on function and processes of ecosystems beyond corals, fish, seagrass and mangroves to include the GBR's other diverse functions would enable understanding of when impacts from climate change will become irreversible.

GBR science is weighted towards the 7% of the Marine Park and World Heritage area that is made up of coral reefs.[23] This is followed by seagrass and fish which, together with corals, have historically been the focus of attention as the key ecological components contributing to the functional health of the GBR. Consequently, these components have also received the most attention in climate change investigations. To understand reef resilience and health, we need to also understand impacts on at least a small subset of invertebrates (e.g. food for fish).

Unknowns remain, especially relating to the GBR's other diverse functions, its stressors and when irreversible impacts from climate change will happen. These will require discussion and prioritisation: what are the key GBR values and what needs protection?

Greater understanding is needed of how the diverse functions of the holistic GBR system are interacting and how they are impacted under potential climate futures.

OPPORTUNITY 1.3

Flow-on effects from a climate-impacted GBR to cultures and customs are rapidly changing and mostly unknown. This makes prioritising where to intervene to protect areas of high cultural value to Traditional Owners difficult. This could be improved by ensuring transdisciplinary knowledge is integrated into prioritisation processes.

Improvements in the availability and accessibility of data could enable a portfolio of diverse interventions that can be scaled. In turn, interventions could contribute socio-economic, biocultural and ecological benefits. Greater alignment across datasets and the northern, central and southern GBR zones will generate bespoke data for improving shared decision-making processes.

OPPORTUNITY 1.4

Indigenous peoples have adapted to a changing GBR, however the rate of change that is being and will be experienced is unprecedented. Traditional Knowledges could provide a framework for managing a changing and adapting GBR.

Australia has an opportunity to be world leading in blending Western science and Traditional Knowledges systems. Indigenous peoples have developed holistic world views over thousands of years. This Traditional Knowledges blurs the boundaries between land and sea, nature and culture, regarding a system like the GBR as a whole.

Indigenous participants suggested that there is opportunity to address the decline of GBR values in a more profound and connected way, using a collaborative approach founded in Traditional Knowledges. There is opportunity for enhancement of existing processes, with clear capacity-building strategies that involve Indigenous peoples at the beginning of the process, rather than only the end. Where appropriate, the inclusion of FPIC and co-design processes should be able to streamline the current complex processes, which can be at odds with Indigenous peoples' world views.

Developing understanding between the two systems requires respect, dignity and sovereignty to Indigenous peoples. Existing precedents for such collaborations include the State of the Environment report (2021),[24] the recently released Reef 2050 Traditional Owner Implementation Plan from the Traditional Use of Marine Resources Agreements (TUMRA),[25] the Strong People – Strong Country Framework,[26] and the emerging Southern Great Barrier Reef Plans of Management,[27] which is positioning Traditional Owners as the leading GBR management group on their Sea Country.

2.

OPPORTUNITY 2.1

Advancing existing research and development programs to develop new interventions will require expanded monitoring and modelling. This can provide information to support decision-making, noting that any prioritisation process should consider the urgency required to develop and deploy interventions.

Resilience indicators that could be captured by monitoring programs in the future include impacts of ocean current, multiple and cumulative stressors, intensity of extreme events, and the scale of and uncertainty in modelling.

OPPORTUNITY 2.2

There is enough knowledge now to ramp up research and development of interventions that will be effective in a high-emissions scenario. Combining interventions will be important for achieving maximum benefits while addressing climate impacts. When designing and implementing new interventions, the presence of existing interventions and potential for interactions could be considered.

Expanding data collection around these components can begin to address the existing knowledge gaps. This is particularly important for the high-emissions scenario, where the historical observational period will be of limited applicability to aid understanding. The recovery potential and ecological functioning of the altered (or new) low-coral-cover systems—likely to emerge under the high-emissions scenario—were identified as areas requiring further research.

3.

OPPORTUNITY 3.1

Standardising and centralising socio-ecological data could aid GBR management. Of particular importance will be understanding differing opinions between groups as to what values, regions or functions are most important for preservation or protection. If we can't save everything, what we can save needs to be communicated and understood by all.

OPPORTUNITY 3.2

Greater alignment of communication strategies between organisations that research and manage the GBR could assist the public in understanding the reality of climate impacts and the risks of intervening and not intervening.[28]

Better public communications would socialise a realistic expected future for the GBR and build public trust and social licence for higher-risk interventions.[29]

OPPORTUNITY 3.3

Relevant research organisations could form a consortium to agree on sector-wide data standards and sharing arrangements. Such agreements would support better integration of existing and future research efforts.

Data sharing and standard formats could become a fundamental requirement for research or operation in the GBR—so that all data is shared and not left to individual relationships. This approach would ensure decision support tools, models and any future digital twin are founded on a dataset that is as extensive as possible. The geographical area and the complexity of the GBR is so great that all possible data sources (including community-based sources) will be needed to get a better understanding of the details of the GBR's state, function and dynamics over time.

OPPORTUNITY 3.4

If suitable regulations and laws are developed that do not rely on political involvement to be implemented in full, a more evidence-informed system would be secured for the benefit of the GBR.

OPPORTUNITY 3.5

A comprehensive review of GBR management may offer opportunities to streamline processes that are currently decentralised to create a management setting that is fit for purpose and agile enough to react to a changing climate.

Since the Great Barrier Reef Marine Park Act (1975)[30] became the accepted framework for GBR management, a complex, multi-tiered governance model has grown incrementally over time. The decentralised model convolutes decision-making processes and impacts how the various management agencies communicate.

The Reef 2050 Plan recognises the importance of good governance to support its implementation and goes some way to addressing the complexity of the system. More could be made of current plans, policies and strategies that aim to address the threats, including, but not limited to: Reef 2050 Plan;[31] Water Quality Improvement Plan;[32] Reef 2050 Traditional Owner Implementation Plan; Queensland Sustainable Fisheries Strategy 2017–2027;[33] and the Reef Wetland Strategy.[34] The broader institutional structures and governance landscape in which they operate includes the on-ground and regional delivery organisations that are exemplified by the Natural Resource Management regional groups.[35]

CONCLUSION

Climate change is the primary threat to the GBR and its connected systems. Scientists expect more severe, irreversible and costly impacts in a high-emissions scenario compared to a low-emissions scenario. Multidisciplinary experts are developing innovative, world-leading and novel interventions that aim to build resilience and adaptation. In the medium-term, there are opportunities to slow the decline in GBR health. However, this requires Australia to act now.

In the near and low-emissions futures, with stronger centralised decision-making processes and greater data integration, there are opportunities to tackle multiple stressors in marine, land and coastal regulatory systems.

The GBR is a global icon and part of the Australian peoples' identity. In recent decades scientists, locals and Traditional Owners have been witnessing the decline of the GBR's condition, health and function. Truthful, open and clear communication with the public is needed to prepare Australians for what is to come, given the GBR will continue to change as the environment becomes more challenging for its habitats and species. Clear communication is also important to garner support for necessary management interventions to protect the GBR to the greatest extent possible.

Informed prioritisation processes will require the inclusion and integration of ecological, socio-ecological and Traditional Knowledges. This could be used to communicate more clearly with the public, guide decision-making and ensure a future for the Great Barrier Reef.

Heart Reef in the Whitsunday Islands. CREDIT: TANYA / STOCK.ADOBE.COM

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GLOSSARY

Catchment—Land that is bounded by natural features like hills or mountains from which all run-off water flows to the same low point. This low point will be a dam, a location on a river or the mouth of a river where the water enters a bay or the ocean.

Climate change—Any change in the climate lasting for several decades or longer, including changes in temperature, rainfall and wind patterns.

Digital twin—A digital (or virtual) twin builds on the idea that information on a physical object or system can be separated from the physical object to form a virtual, information replica of the physical system.[36] A digital twin typically consists of the physical object or system, a virtual model that represents it, and a set of data streams that update the system based on real-time information and mirror the state of the physical twin.[37] Digital twins are already used on small scales on the GBR to model the behaviour of specific species, habitats or ecosystems.

Extreme event—Unusual weather or climate event constituted of intense environmental conditions in a given location measured through relative (e.g. beyond 90th percentile) or absolute (e.g. above 35°C) thresholds in parameters (e.g. air temperature, water temperature, wind speed, etc.).

Forecast—The best projection or prediction about the future given by one model or one expert (e.g. weather forecast).

Foresight—A construction about the future, with the aim to prepare for it, imagining the implications of possible futures. There is a strong link with management and decision-making (e.g. technology foresight).[38,39]

Horizon scanning—A means to foresee events and be prepared to prevent failure from identifying and exploiting opportunities, often in the early phases of activities.[40-43]

Intervention—A specified set of activities designed to put into practice an activity of known dimensions.[1]

Prediction—A statement about what is thought will happen, for example about natural conditions, in the future, often associated with probability distributions. The main characteristics of future predictions are their degree of certainty, which lead to only one prediction (compared to the multiplicity of scenarios). Many authors use this term to describe the result of a modelling exercise based on a set of assumptions (e.g. predictions of potential distribution areas).

Projection—A statement about what would happen, based on the extrapolation of past and current trends (e.g. projections of future climate, population projections).

Scenario—A plausible description about alternative futures, based on a coherent and internally consistent set of assumptions about key relationships and driving forces. Scenarios include one or several storylines, and may also include modelling results (e.g. climate scenarios).

Storyline—A coherent story (narrative) about what may happen in the future that is a consistent unfolding of past events, or of plausible future events or pathways.[14,44]

Traditional Owner—Aboriginal and Torres Strait Islander peoples, for example of the Great Barrier Reef Land and Sea Country who have ongoing traditional and cultural association with the land and sea, and possess rights and interests under Traditional Laws, Customary Lore, and Australian and Queensland Government laws.

Traditional Knowledges—A cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment.

Uncertainty—A measure of confidence that the data is an accurate description of reality, based on its variability.

Hill Inlet at Whitehaven Beach, Whitsundays. CREDIT: CORAL BRUNNER

APPENDICES

Appendix A: Organisations participating in the roundtables

Of the 285 roundtable participant nominations, 54% were invited, of which 25% were unable to attend, and 29.4.% attended in person or online, with an average 28 participants at each session. Fields of expertise varied across the course of the three roundtables dependent on the scope of discussion and availability of nominees. The representation across all three roundtables was from the following organisations:

Adelaide University	Queensland Department of Environment and Science
Australian Centre for Robotic Vision	Queensland Indigenous Womens Ranger Network
Australian Institute of Marine Science	Reef Advisory Committee
Bureau of Meteorology	Reef and Rainforest Research Centre
Burnett Mary Regional Group	Reef Restoration and Adaptation Program
Climate Change Cluster	Southern Cross University
CSIRO	Taronga Conservation Society Australia
Cook Shire Council	The Australian Academy of Science
Dawul Wuru Aboriginal Corporation	TropWATER, James Cook University
Girringun Aboriginal Corporation	University of New South Wales
Great Barrier Reef Foundation	University of Queensland
Great Barrier Reef Marine Park Authority	University of Tasmania
Griffith University	Queensland University of Technology
James Cook University	Yuku Baja Muliku Land Corporation.
Koinmerburra	

From the attendee data from the roundtables, we have identified the representation of Indigenous or Torres Strait Islander peoples and gender representation. Overall, gender representation was spilt with 61% men and 39% women. This is a higher representation of women than the industry average where women make up 20% of marine-science-related roles.[45] Roundtable One had 96 nominations (61% identified as men, 39% identified as women, 6% identified as Indigenous). Of these, invitations were extended to 33 people (66% identified as men and 34% identified as women, 9% identified as Indigenous) with an attendance of 26 participants (69% identified as men and 31% identified as women, 12% identified as Indigenous). Roundtable Two had 108 nominations (65% identified as men and 35% identified as women, 7% identified as Indigenous). Invitations were extended to 40 people (58% identified as men and 42% identified as women, 17% identified as Indigenous) with an attendance of 29 participants (41% identified as women and 59% identified as men, 17% identified as Indigenous). Roundtable Three had 81 nominations, 59% identified as men and 41% identified as women, 12% identified as Indigenous). Invitations were extended to 46 people (44% identified as women and 56% identified as men, 11% identified as Indigenous) with an attendance of 29 participants (55% identified as men and 45% identified as women, 14% identified as Indigenous).

Appendix B: Methods, surveys and questionnaires

Multiple lines of evidence, using mixed methods, were coded to identify common themes from three roundtables and provide the data for this report. Surveys and online interactive questionnaires were used to assist the roundtable process to collect qualitative and quantitative data from participants regarding their views, understanding and knowledge on a range of topics.

All qualitative data were coded in NVivo 12 and the numerical values were analysed. Participants' expert contributions were coded into topics that were most often mentioned. For the roundtables, the pre-survey and interactive qualitative questions were free-form text. Restricting the results to numerical values was a consequence of using open-ended questions with free-form text rather than seeking agreement on prescriptive answers (i.e. a set of drop-down options). Contributions at the roundtable discussion were individual and were not put for a vote to get agreement among the group. Assumptions cannot be made that the entire group agreed on the discussion points from the interactive online questionnaire responses.

SURVEYS

Surveys were used prior to the roundtable meetings to provide stimuli and provocation for roundtable discussions.

Roundtable One

The survey for Roundtable One stated the ecosystem complexes, as defined by GBRMPA, grouped into marine and terrestrial habitats, as well as climate scenarios for 2040 and 2060. The questions throughout the survey refer to these classifications and definitions.

- Participants were asked to list ecological components contributing to the functional health of the GBR. These ecological components were categorised by taxonomic group, habitat, ecosystem and process. Each of the listed ecological components were linked to a degree of impact under each respective climate scenario. The degree of impact was chosen categorically from a drop-down menu, with the options of 'low', 'medium', 'high' or 'uncertain'.
- For each of the eight ecosystem complexes, participants were asked to rank the primary stressors in order of importance. Stressors reflected the key pressures listed by GBRMPA (climate change, poor water quality, coastal development impacts, impacts from fishing) and included the 'almost certain' threats with 'catastrophic' and 'major' consequences as identified in the 2019 Outlook report. These stressors were provided in a drop-down menu, and an option for 'other' was provided, with space to describe an alternative stressor.

Participants were asked to list critical processes affected under each climate scenario, and to classify these processes as 'physical', 'ecological' or 'chemical'. The degree of impact in each climate scenario was chosen categorically from a drop-down menu, with the options of 'low', 'medium', 'high', or 'uncertain'.

- Free-form text entry was provided for participants to describe any knowledge gaps, and why there were gaps in these places.

Roundtable Two

The survey for Roundtable Two focused on reef interventions.

1. Respondents were asked to list known reef interventions, and assign a phase of deployment or development from a drop-down menu. Phase options included 'currently deployed', 'in R&D', and 'not being considered'.
2. Effective and obsolete interventions across the three climate scenarios previously defined were listed by respondents. This included interventions and technologies that may become effective in future scenarios.
3. Knowledge gaps that could impact the development of reef interventions were listed, in combination with strategies (if known) that may be needed to fill these gaps.
4. Scaling and integration were explored through a series of questions.
    a. Interventions within participants' expertise were listed, along with enablers and barriers to their deployment and scalability.
    b. Mutually beneficial and conflicting reef interventions were explored. For each of these, participants listed combinations of interventions that may generate impact, including an explanation of the potential impact(s).

Roundtable Three

Roundtable Three was preceded by a survey that was focused on a series of provocations. These provocations were headed by an introductory statement.

A view emerged in the first two roundtables that communication about the GBR and its condition to Australians, particularly to those who would be most directly affected by its degradation, was seriously underplayed. Descriptors such as 'truth' and 'integrity' were used, as was the idea that the provision of information and options would allow the community the dignity of making informed decisions.

By contrast, words such as restoration could be seen as encouraging false hope—especially when applied to 'the' GBR. It appears extremely unlikely that 'the' GBR can be restored to something resembling the GBR we knew just a few decades ago.

The survey was intentionally designed to include confronting questions in order to provoke thought and discussion in the final roundtable discussions. The survey included the provocations presented in the survey and Slido, with the questions outlined below.

The state and composition of the GBR is acknowledged as dynamic—having changed and adapted over time. Roundtable comments also acknowledged that different species have varying abilities to adapt to environmental changes. This 'adaptive capacity' may be enough to uphold the resilience of critical GBR functions, though not all functions. This changing environmental state may eventually reach an equilibrium without human intervention.

While it could adapt, we are in uncharted territory. The level of atmospheric CO_2 is higher now than at any time in the past 800,000+ years and the rate of its increase is unprecedented. The resulting changes are frightening: rising sea levels; ice and glacier melts; extreme weather events; and acidification of oceans and lakes, to name a few.

- Participants had a binary response choice of whether they thought that we should 'intervene', or 'not intervene'.
- Participants listed what there was to lose and gain if we intervene.
- Participants listed responses in a matrix addressing how we know when and where to intervene and not intervene.
- Participants listed reasons for rewilding, and whether developing a virtual reef could provide new levels of understanding

Discussion in the previous roundtables painted a dire picture of what may be able to be preserved or maintained in the medium-term future, particularly in a high-emissions scenario.

1. Participants provided a binary (yes, no) response to whether we should:
    a. aim to protect a subset of the GBR
    b. define this subset by tourism and cultural purposes.
2. If participants chose that the subset should not be defined by tourism and cultural purposes, they could provide an explanation of their subset definition.

The GBR is susceptible to multiple stressors, some of which are fuelled by global warming. Importantly, managing the GBR is also about managing the adjacent land and its use.

3. Participants were asked whether they agreed with revising the GBR Management Zone to encompass an area from the source of catchments to deep water, and include their reasoning.
4. Participants were asked whether they agreed with 're-wilding' the GBR and catchments, and their reasoning.

Declaration of a comprehensively managed GBR Management Zone would require new (and enforced) planning and regulatory provisions to, stop coastal development, improve land-use measures, and implement nature-positive solutions in the Reef Management Zone.

5. Participants indicated their agreement or lack thereof to comprehensively review GBR management, via a yes/no response accompanied by their reasoning.

Roundtables one and two highlighted the siloed nature of different areas of research. In the pursuit of holistic and better integrated modelling, a digital twin was defined and suggested as a tool for GBR management.

6. Participants were asked whether they agreed that we should develop a digital twin for the GBR, and their reasoning.
    a. In reference to developing a digital twin, participants were asked to rate the necessity of various resources, technology, data, and infrastructure (including collaboration). These were graded on a scale of 0 (not needed) to 10 (strongly needed). Participants could list any additional factors that were not provided, and rate their grade on a similar scale.

ONLINE INTERACTIVE SLIDO QUESTIONS

In each of the three roundtables, expert discussions were accompanied with an open-text survey through the online tool Slido (https://www.slido.com). This aimed to collect wider input from all participants, giving everyone the opportunity to contribute without relying on limited speaking time. The Slido questions aligned with the main objectives of each roundtable, covering, for example,

current knowledge, implications of the different climate scenarios, and gaps (including knowledge gaps) that inhibit action. The participants' responses to Slido were downloaded and checked for duplicates in participants and further anomalies (e.g. removing data from non-participants). Remaining responses were collated, de-identified, and analysed through inductive coding (i.e. without preconceived categories) using the qualitative data analysis software NVivo 12.

Roundtable One

To enrich discussions on the diverse climate change impacts on the GBR under different scenarios, participants were asked:

- to provide examples of how existing climate impacts are impacting the ecological, social or cultural functions of the GBR
    - **a.** what knowledge gaps exist about how climate change is currently impacting the ecological, social or cultural functions of the GBR
- what are some examples of impacts to the ecological, social or cultural functions of the GBR that start to occur in a low-emissions future
    - **a.** where knowledge gaps exist
    - **b.** what damage we could potentially prevent in a low-emissions future if we didn't have these knowledge gaps
- what are some examples of impacts to the ecological, social or cultural functions of the GBR that start to occur in a high-emissions future (that weren't present in or have changed from the low-emissions scenario)
    - **a.** where knowledge gaps exist
    - **b.** what damage we could potentially prevent in a high-emissions future if we didn't have these knowledge gaps
- how different climate impacts interact or compound to affect GBR values and function
- what cascading risks can be identified that haven't yet been discussed
- if there were knowledge gaps or other aspects that hadn't been mentioned.

Roundtable Two

Throughout Roundtable Two, participants were asked to answer the following Slido questions:

1. What are examples of Reef-specific or regionally specific interventions?
2. In a low-emissions scenario, where should interventions be targeted to protect the functioning of the GBR (including socio-ecological functioning)?
3. What interventions remain viable in the high-emissions scenario?
4. Are there any additional examples of combining interventions for compounding impact you would like to include?
5. Are there conflicts that are missing?
6. Would any of these enablers be different in the medium-term scenarios?
7. What would be the key barriers to deployment in the medium-term scenarios?
8. What is the most critical knowledge gap that exists regarding deployment of future interventions?
9. In an imaginary perfect world where money and regulatory barriers didn't exist, which intervention would you pursue?

Roundtable Three

To support the synthesis discussions in Roundtable Three, participants were asked to respond to the following questions on Slido:

1. If a subset of the Reef was selected to be the focus of protection efforts, how would that subset be defined?
2. What should be the priorities for urgent action?
3. Where are knowledge gaps preventing informed action?
4. Why shouldn't we develop a digital twin?
5. If we were able to improve our real time monitor and modelling capability, what benefits would there be for the Reef?
6. What action, intervention or management strategy would support the largest range of Reef functions?
7. What does the public not understand about the Reef, that they need to?
8. Who should be responsible for this communication?
9. Risk appetite and social license for intervening
10. How do we influence policy and action?
11. Should there be an independent review of the ability of Reef management to deal with climate change?
12. Final responses